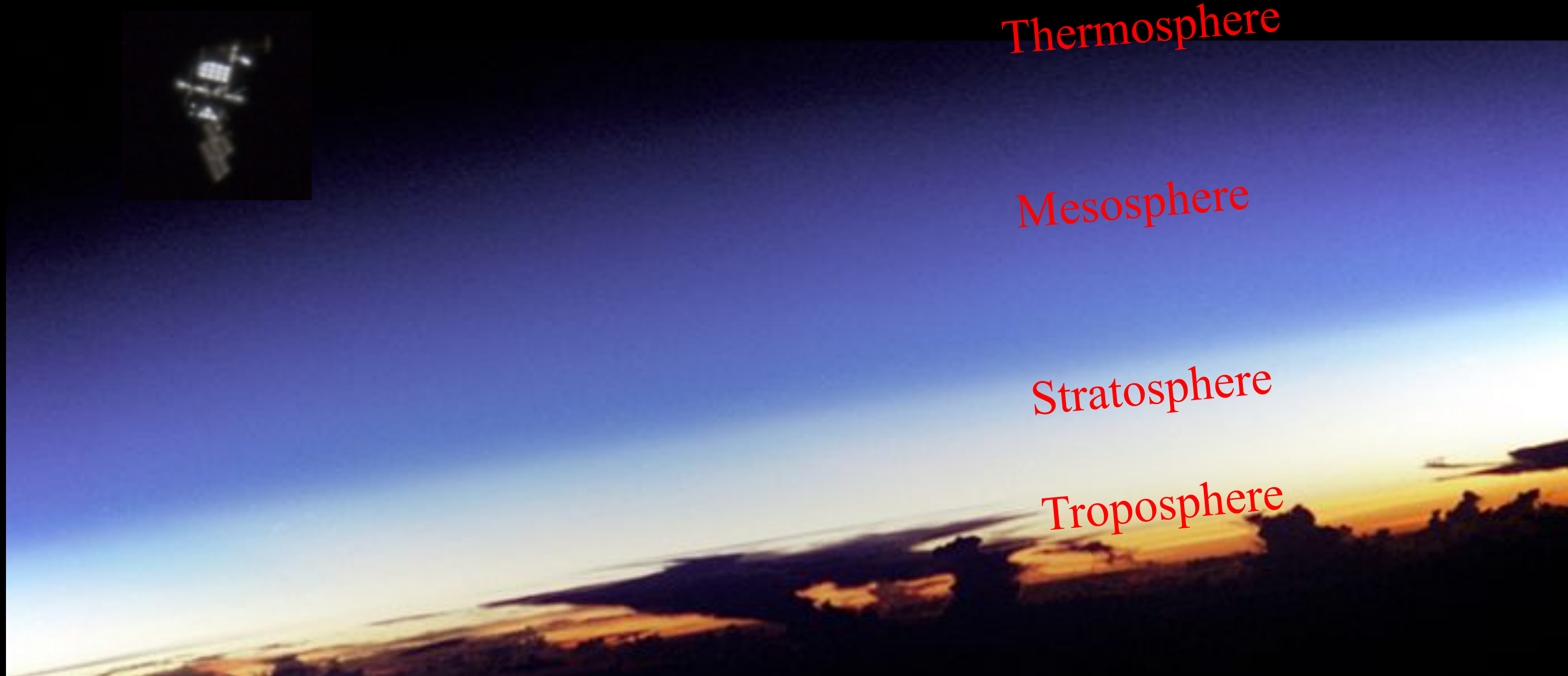
Space Weather in the Thermosphere: Satellite Drag



Given by Yihua Zheng for 2014 summer bootcamp

Prof . Delores Knipp
University of Colorado Boulder

Space Weather Training for Mission Operators and Engineers, January 2014

Space Weather in the Thermosphere: Satellite Drag

Motivation:

- Track and identify active payloads and debris
- Collision avoidance and re-entry prediction
- Attitude Dynamics
- Constellation control
- "Drag Make-Up" maneuvers to keep satellite in control box
- Delayed acquisition of SATCOM links for commanding /data transmission
- Mission design and lifetime

- Study the atmosphere's density (and temperature) profiles

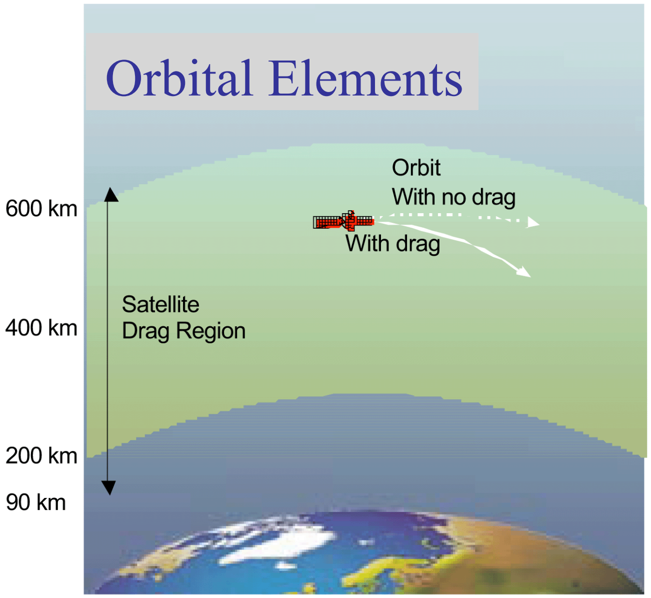
Overview

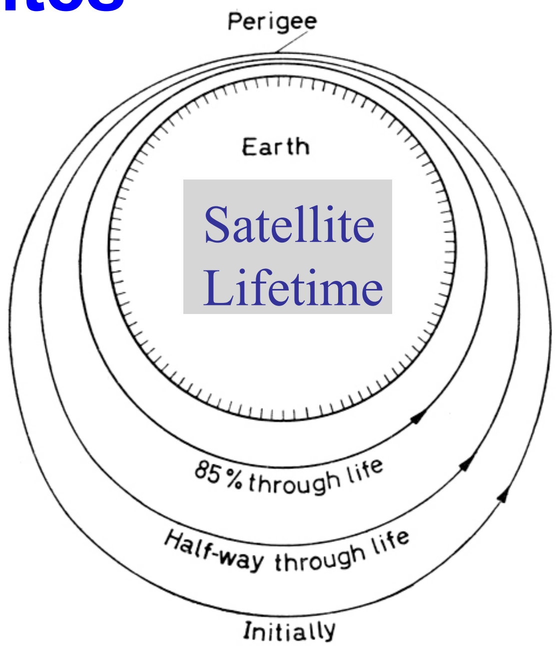
- Fundamentals of Satellite Drag
- Thermosphere and Its Characteristics
- Dynamic Space Weather Drivers
- Collision Avoidance
- Help from CCMC

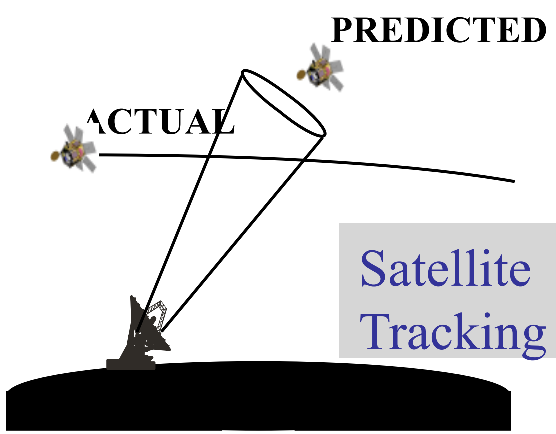
Spacecraft Drag

- Spacecraft in LEO experience periods of increased drag that causes them to speed-up, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude in an atmospheric region called the thermosphere.
- Drag increase is well correlated with solar Ultraviolet (UV) output, and atmospheric heating that occurs during geomagnetic storms. Recently lower atmospheric tidal effects have been modeled in satellite drag response.
- Most drag models use solar radio flux at 10.7 cm wavelength as a proxy for solar UV flux. Kp/Ap are the indices commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft.
- Very high UV/10.7 cm flux and Kp/Ap values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.

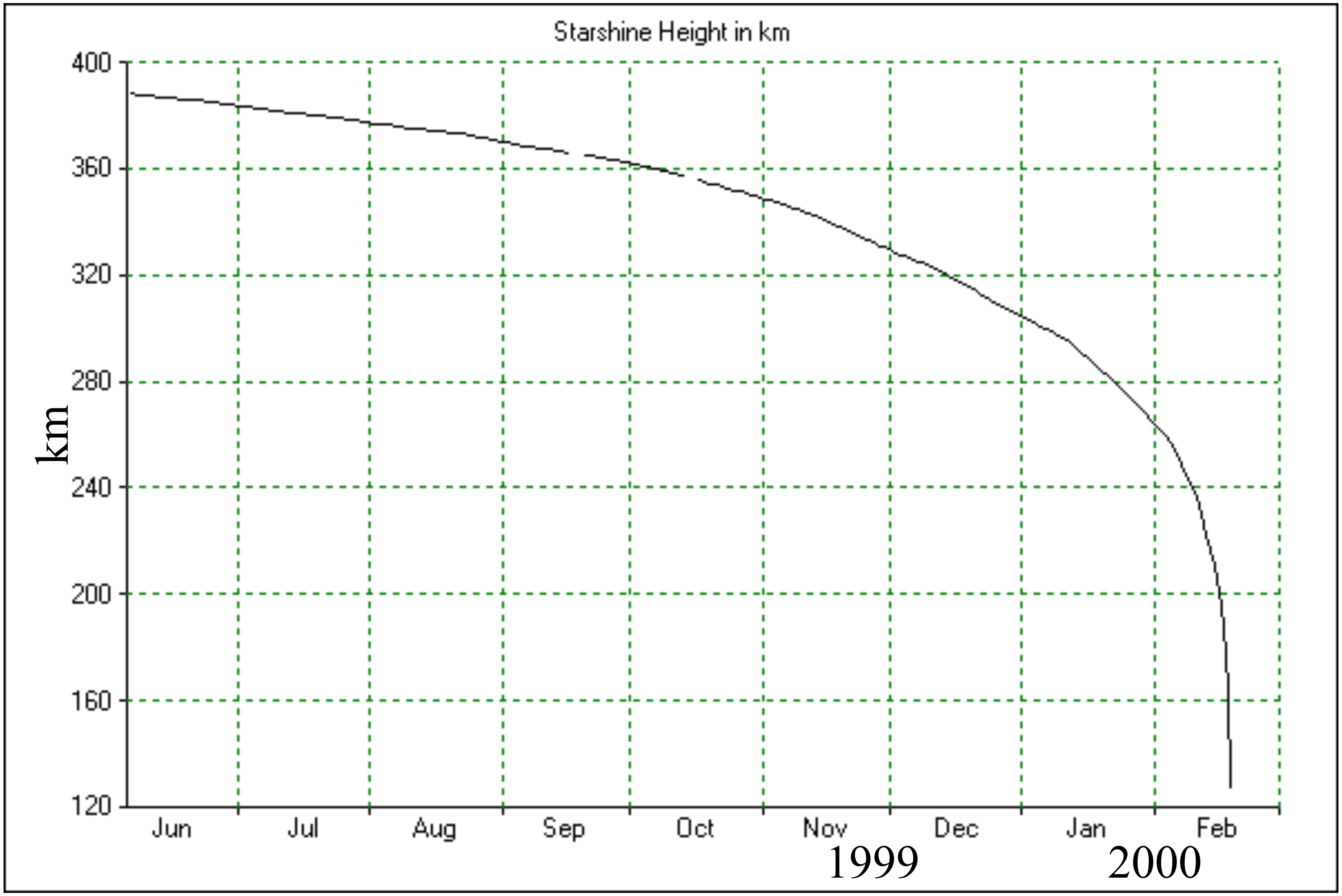
Atmospheric Drag on Satellites







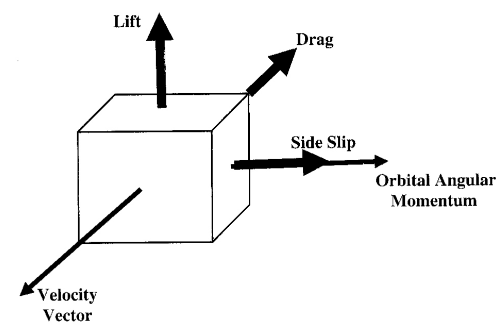
STARSHINE-1 Height vs Time Profile



Satellite Drag and Thermosphere Density

Aerodynamic forces are the forces created by a spacecraft's movement through a neutral density atmosphere. The forces result from momentum exchange between the atmosphere and the spacecraft and can be decomposed into components of lift, drag, and side slip.

$$\boxed{F_i = A C_i \tfrac{1}{2} \rho v^2}$$



$F_i =$ Force, N

i = d(drag), l(lift), and s (side slip)

$A =$ area, m^2

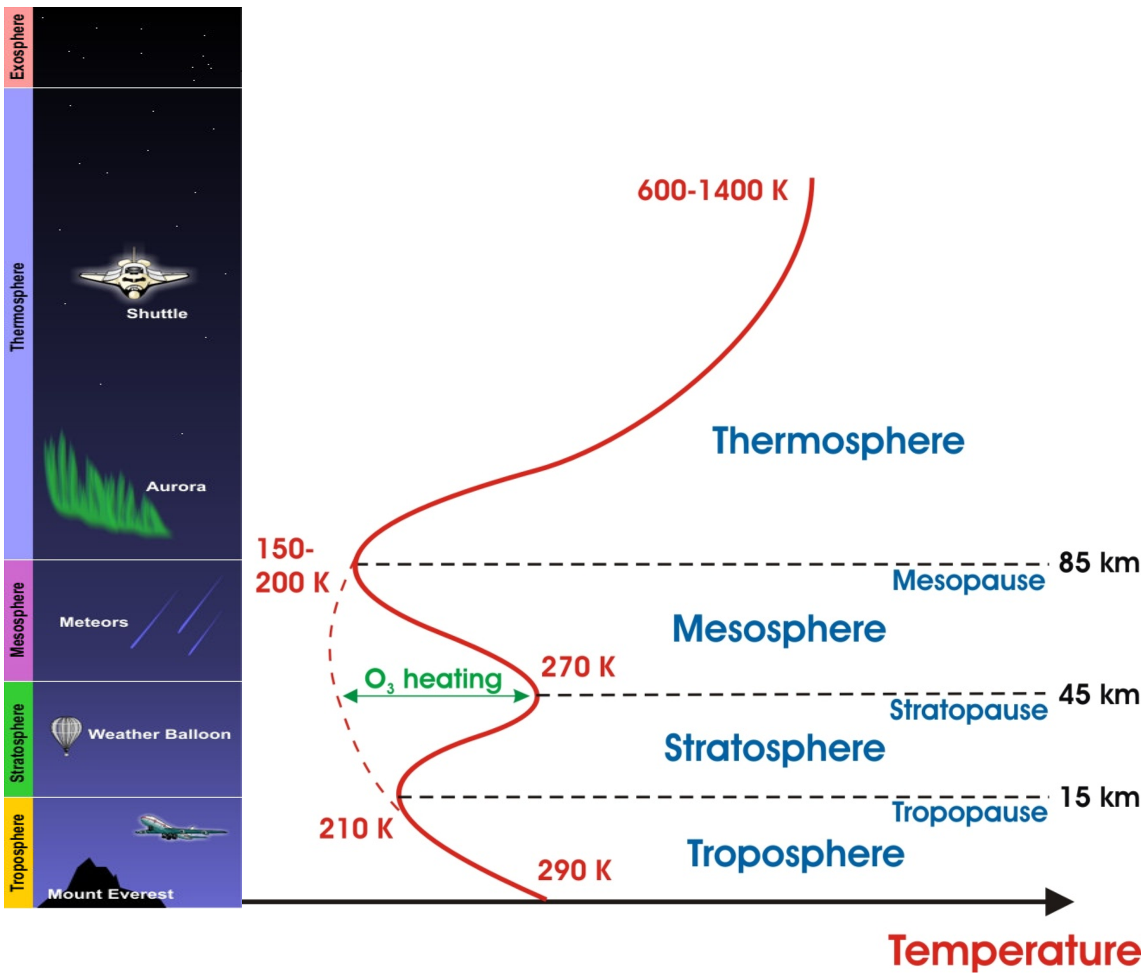
$C_i =$ coefficient

$v =$ spacecraft speed with respect to the atmosphere, m/s

$\rho =$ atmospheric mass density, $kg\,m^{-3}$

In the thermosphere the density is a function of temperature

Upper Atmosphere – Thermosphere

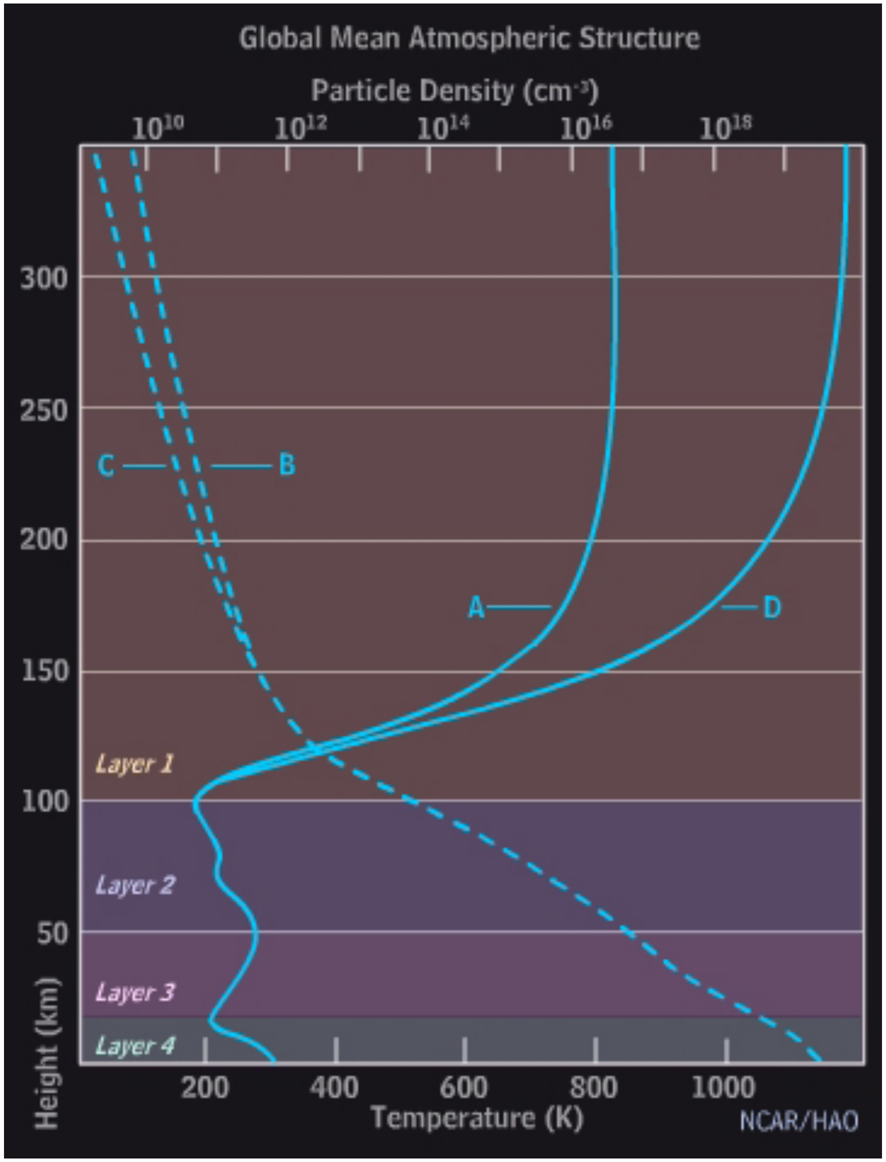


The outer gaseous shell of a planet's atmosphere that exchanges energy with the space plasma environment: **Thermosphere**

- **Energy sources**:
  - Absorption of Extreme UV radiation (10 -200nm)
  - Joule heating by electrical currents
  - Particle precipitation from the magnetosphere
  - Dissipation of upward propagating waves (tides, planetary waves, gravity waves)

- **Energy sinks**:
  - Thermal conduction into the mesosphere
  - IR cooling by CO_2 NO, O
  - Chemical reactions

Thermosphere Variability and Time Scales



Thermosphere:

- **Characteristics**
  - Very high temperatures, often exceeding 1000 k
  - Low neutral density
  - Matter sorted by gravity—heavier material at base
  - Dominated by atomic oxygen

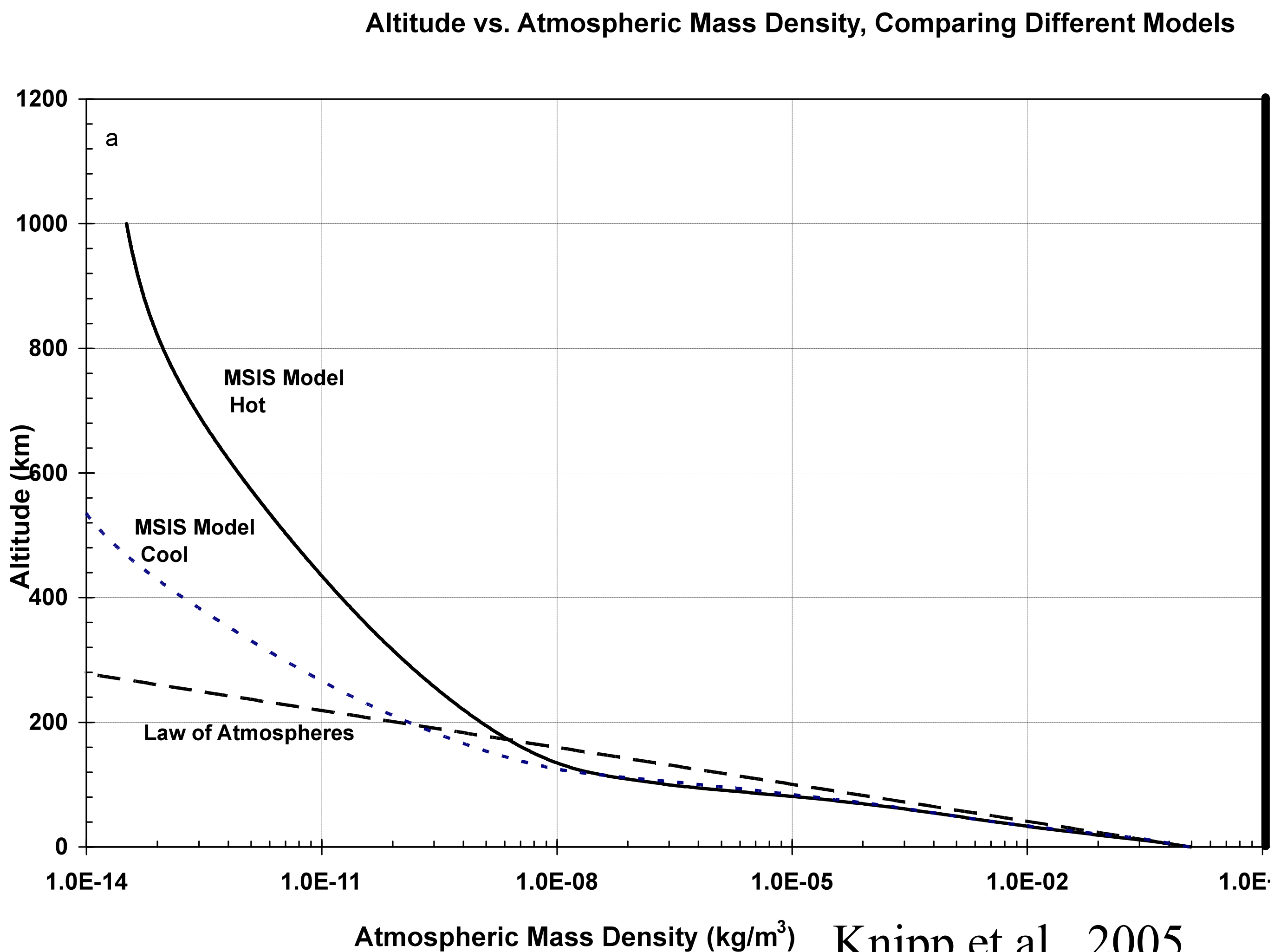
- **Time Scales**
  - Solar cycle
  - Annual
  - 27 day
  - Equinoctal
  - Day /night

A Solar Min Temperature
B Solar Max Temperature

C Solar Min Density
D Solar Max Density

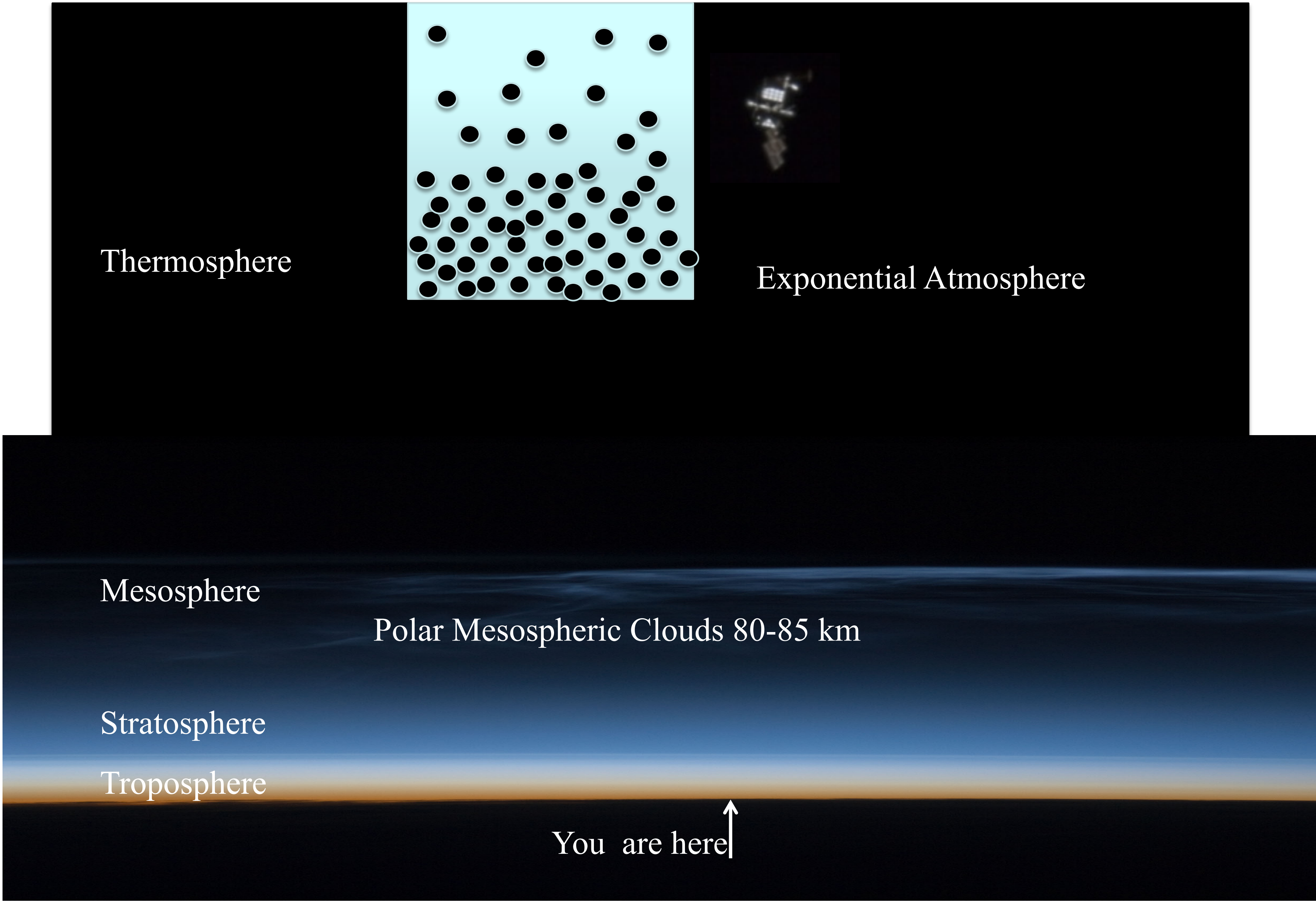
Courtesy of UCAR COMET

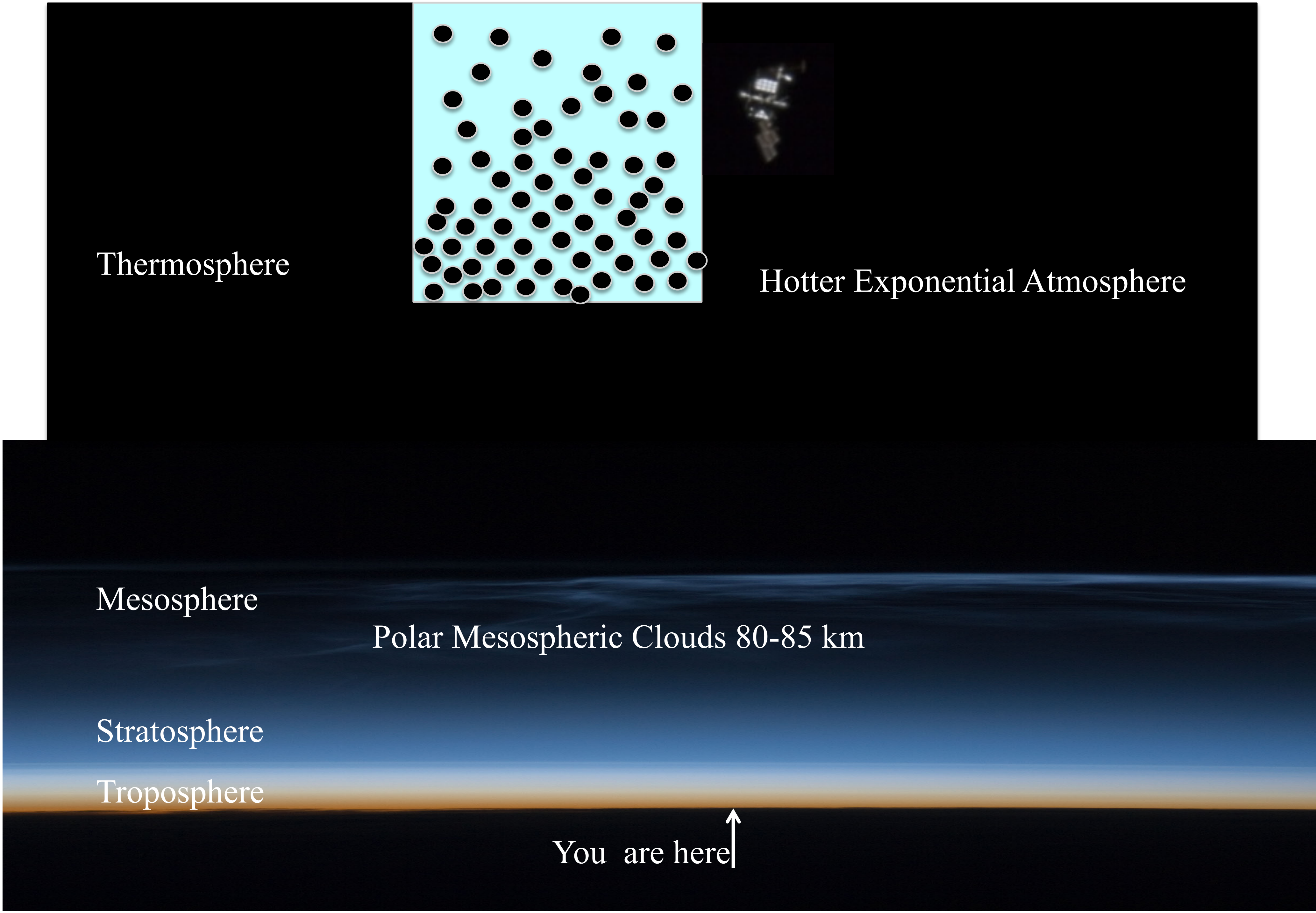
Ideal and Model Atmosphere Neutral Density



Knipp et al., 2005

http://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php

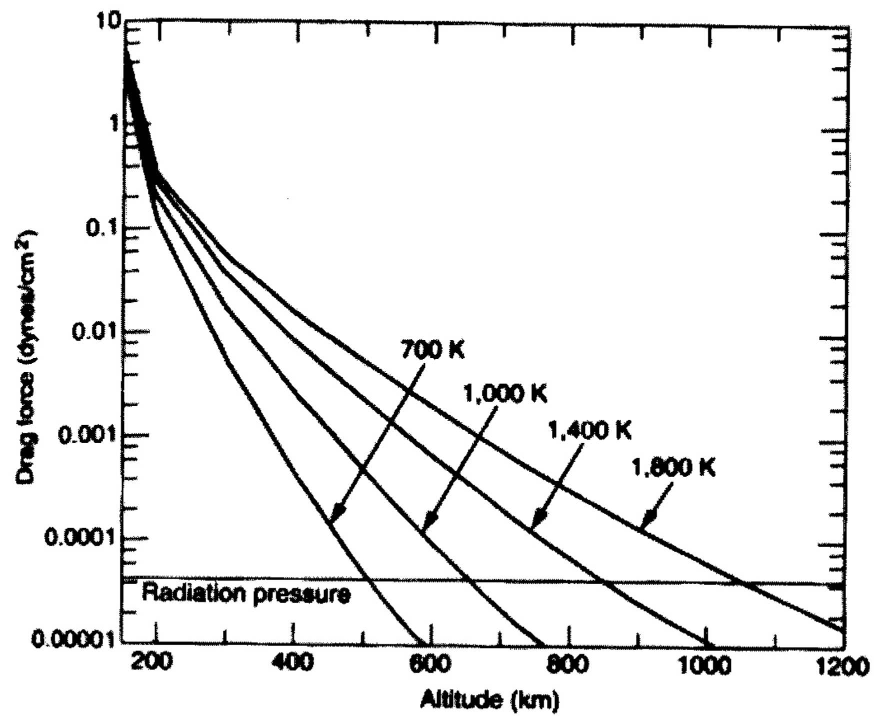

Thermosphere
Exponential Atmosphere
Mesosphere
Polar Mesospheric Clouds 80-85 km
Stratosphere
Troposphere
You are here


Thermosphere
Hotter Exponential Atmosphere
Mesosphere
Polar Mesospheric Clouds 80-85 km
Stratosphere
Troposphere
You are here

Satellite Drag and Thermosphere Density

The drag force is considered the most dominant force on low-earth orbiting spacecraft and serves to change the energy of the spacecraft through the work done by the drag force.

$$\boxed{\frac{dE}{dt} = F_d \circ v = -\tfrac{1}{2}\rho C_d A v^3}$$



F_i = Force, N

i = d(drag), l(lift), and s (side slip)

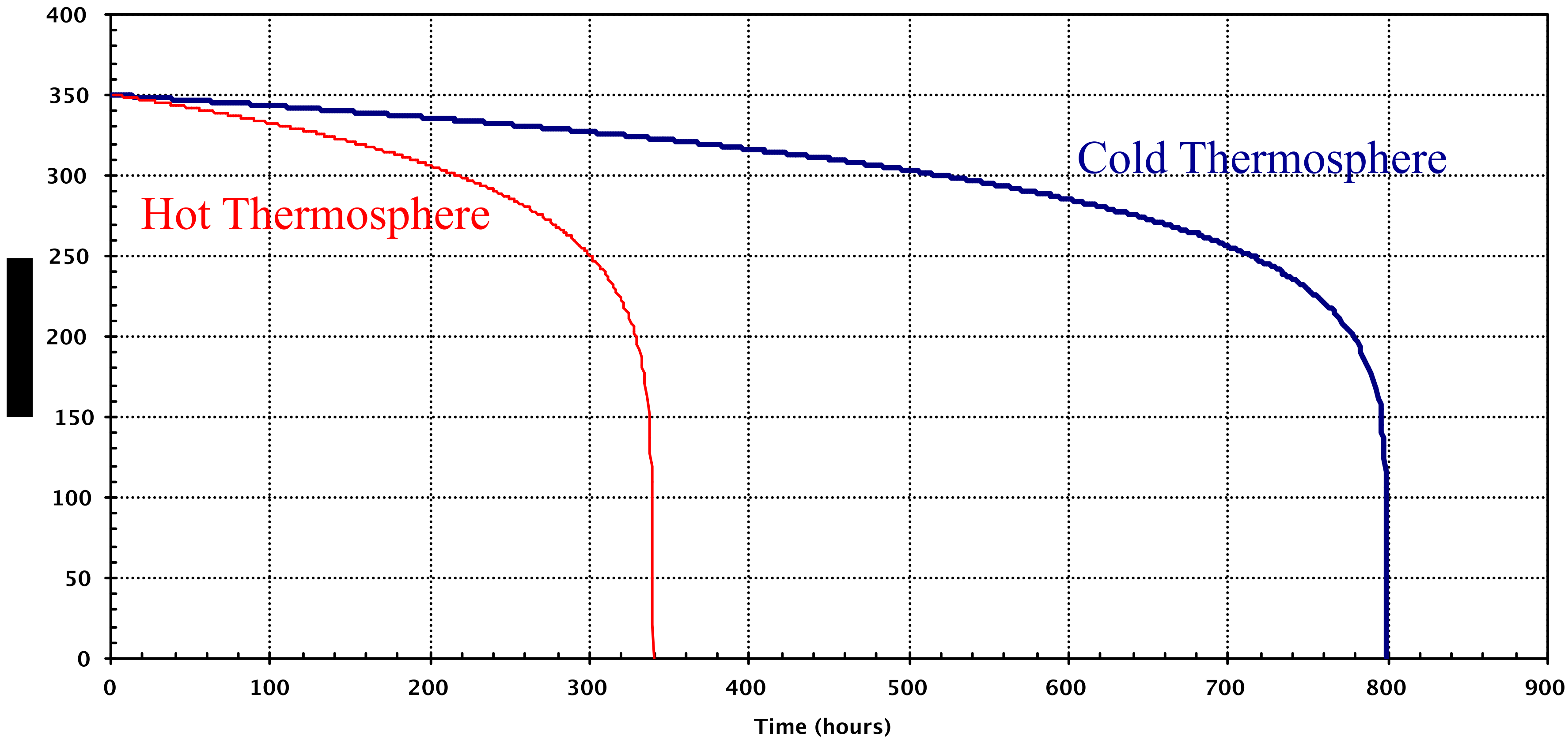
A = area, m^2

C_i = coefficient

v = spacecraft speed with respect to the atmosphere, m/s

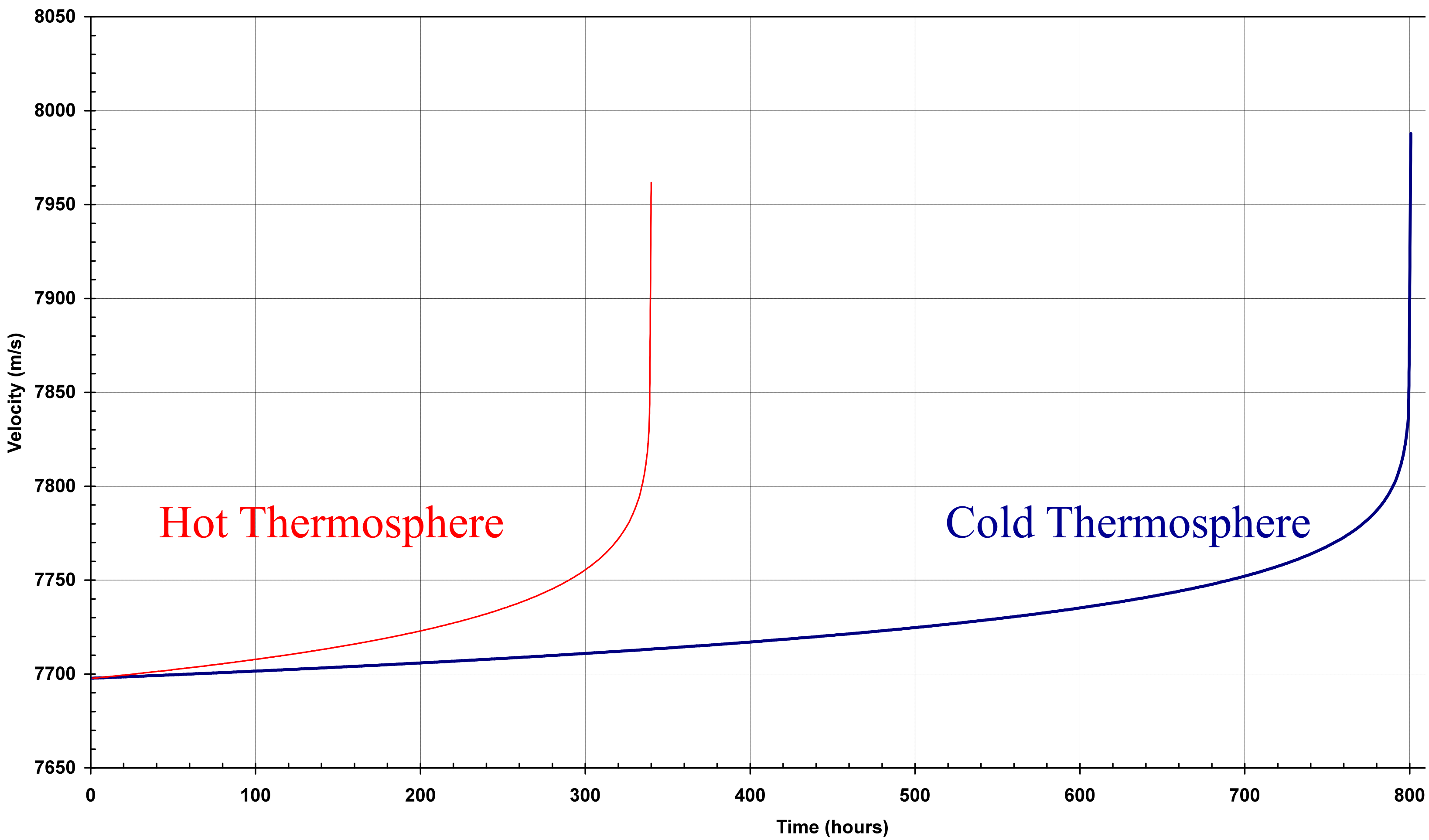
ρ = atmospheric mass density, $kg\,m^{-3}$

“Toy” Model Satellite Altitude vs Time



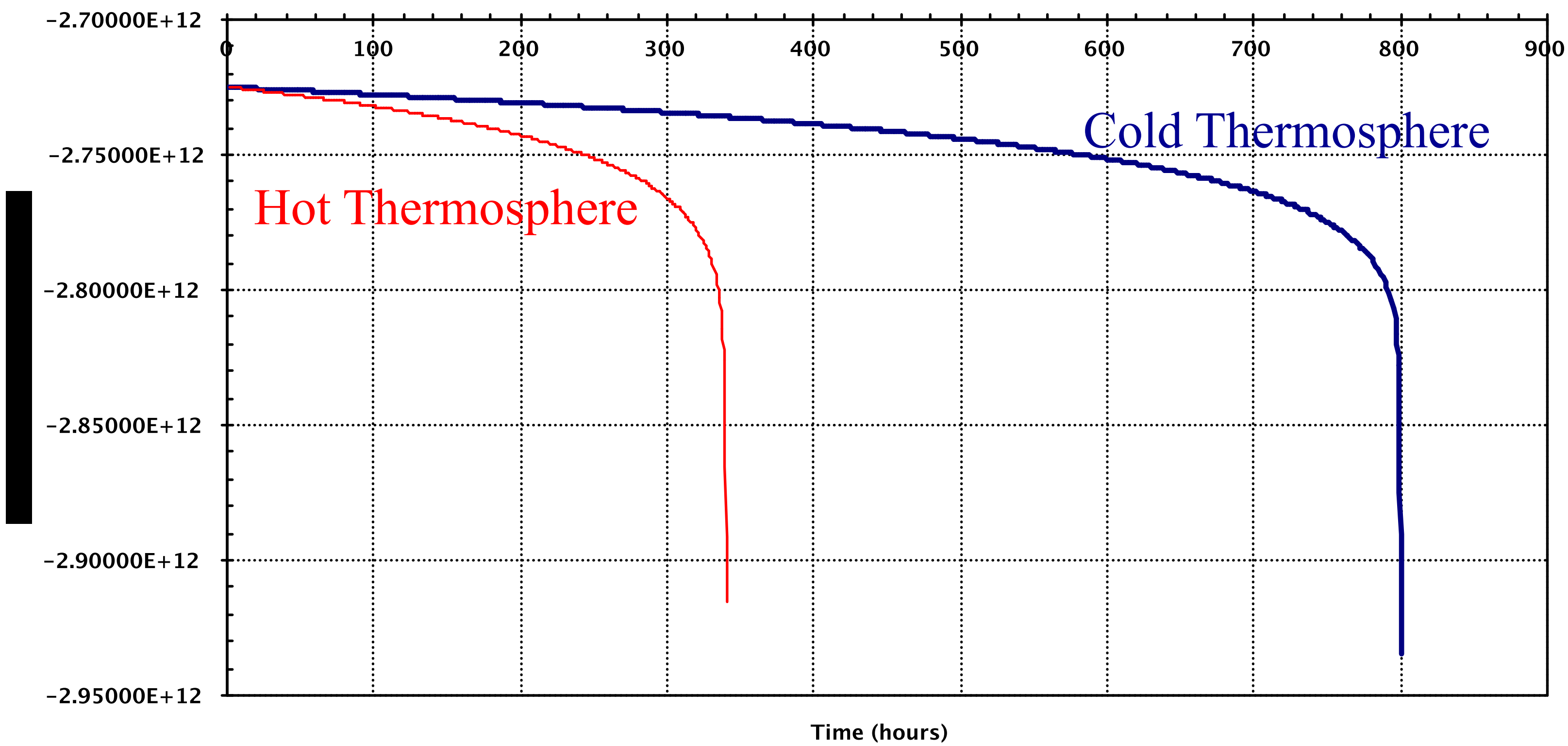
Longer on-orbit lifetime in “cold” thermosphere

“Toy” Model Satellite Speed vs Time

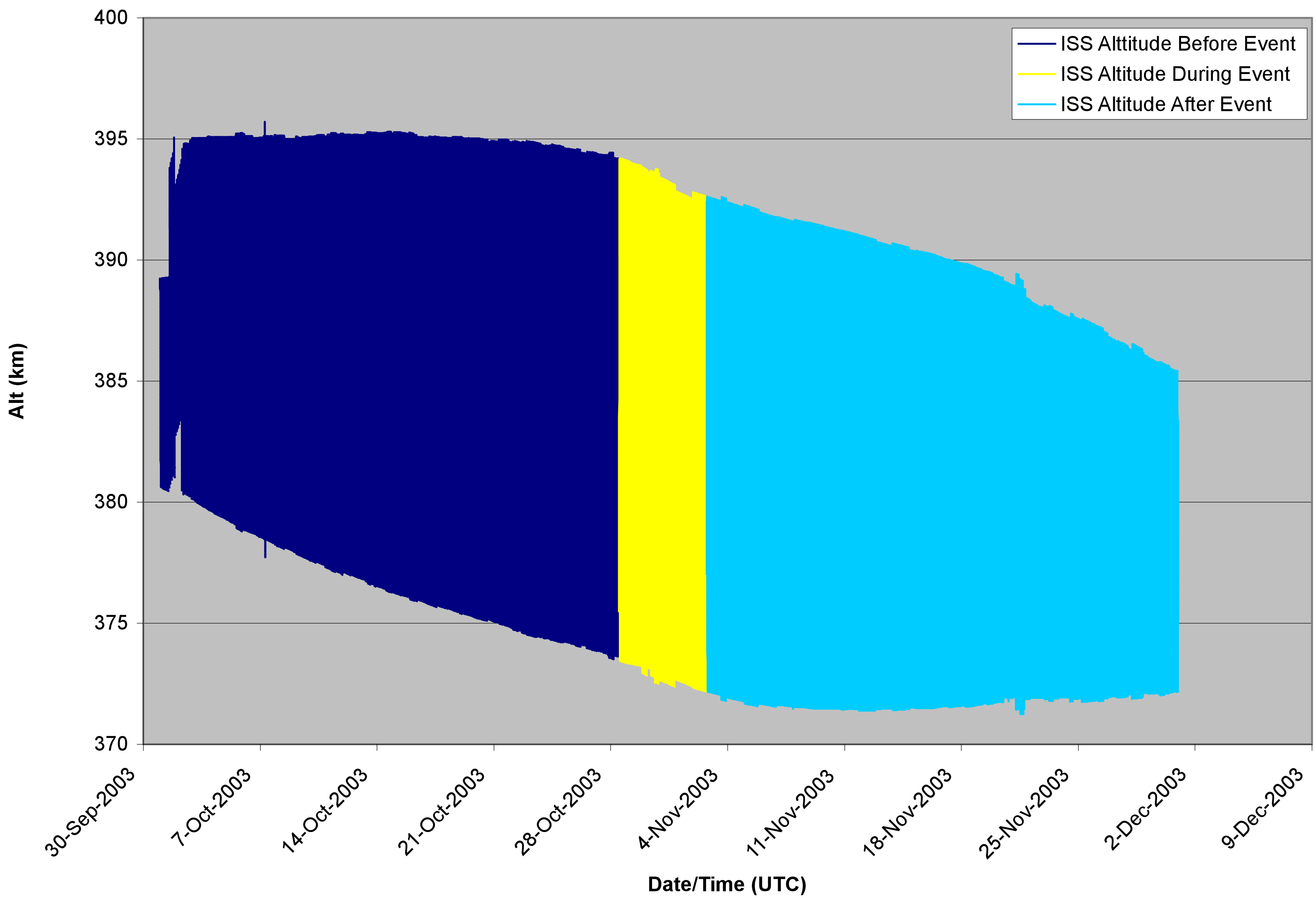


Large reservoir of potential energy, some is converted to kinetic energy

“Toy” Model Satellite Mechanical Energy vs Time



ISS Altitude Oct-Nov 2003



Orbital Period Dependence on Thermosphere Density

Through Kepler's laws, one can derive the rate of change of orbital period (T) in terms of the atmospheric density:

$$\boxed{\frac{dT}{dt} = -\frac{3}{2} B \rho_P \int \frac{\rho}{\rho_P} ds}$$

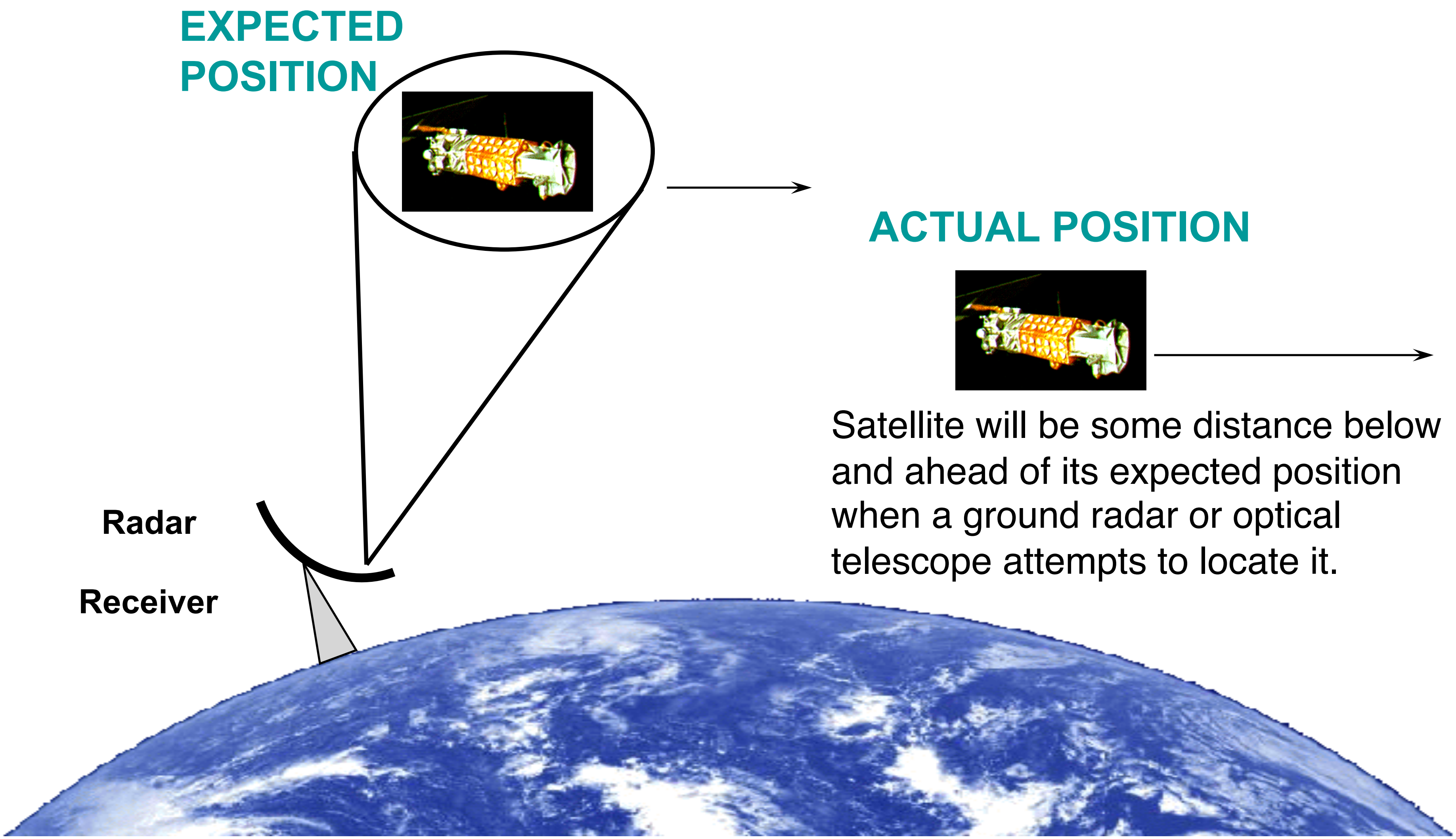
where B = B-factor (ballistic coefficient) = $\dfrac{C_D A}{m}$

ρ_P	=	density at perigee
ρ	=	density
s	=	satellite path

•From radar tracking, one can derive the thermosphere density

•From satellite accelerometers, one can derive the thermosphere density

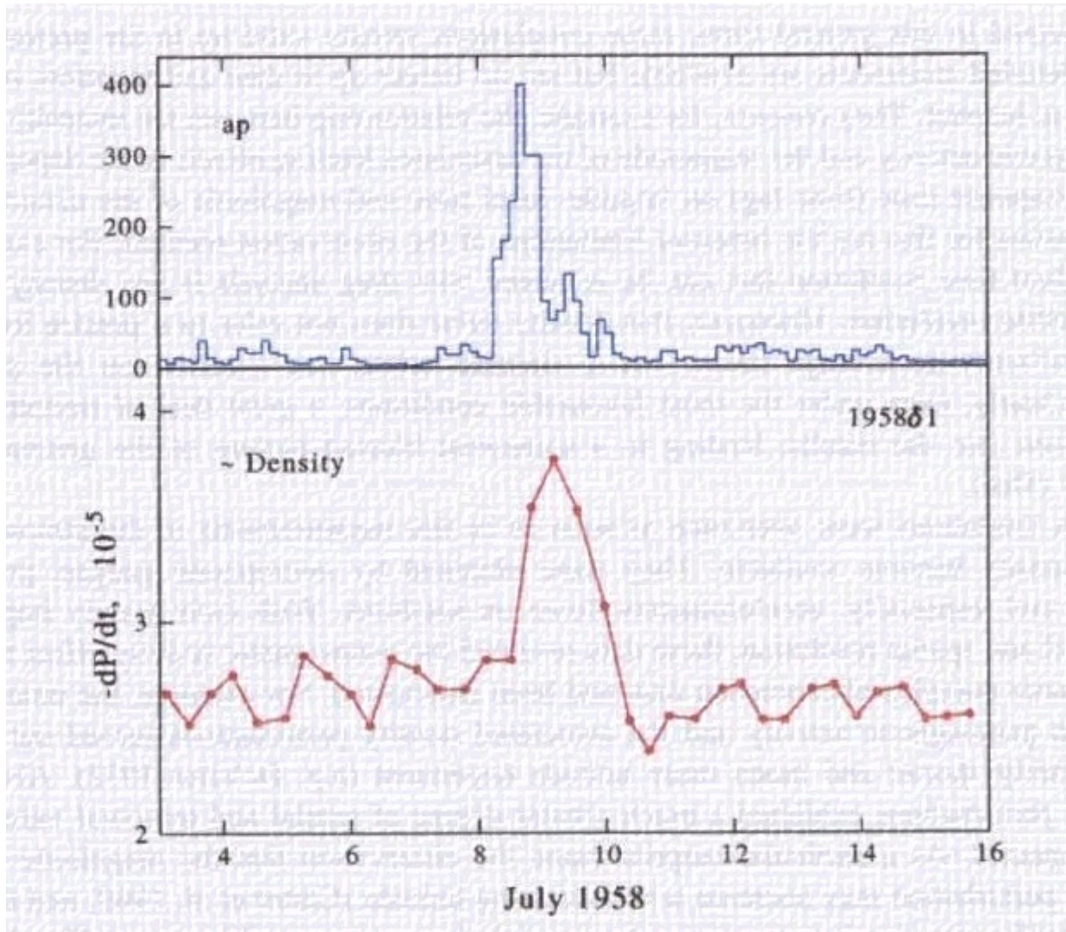
Atmospheric Drag = Space Object Positioning Error



First Observation of Satellite Drag Associated with Neutral Density Enhancement

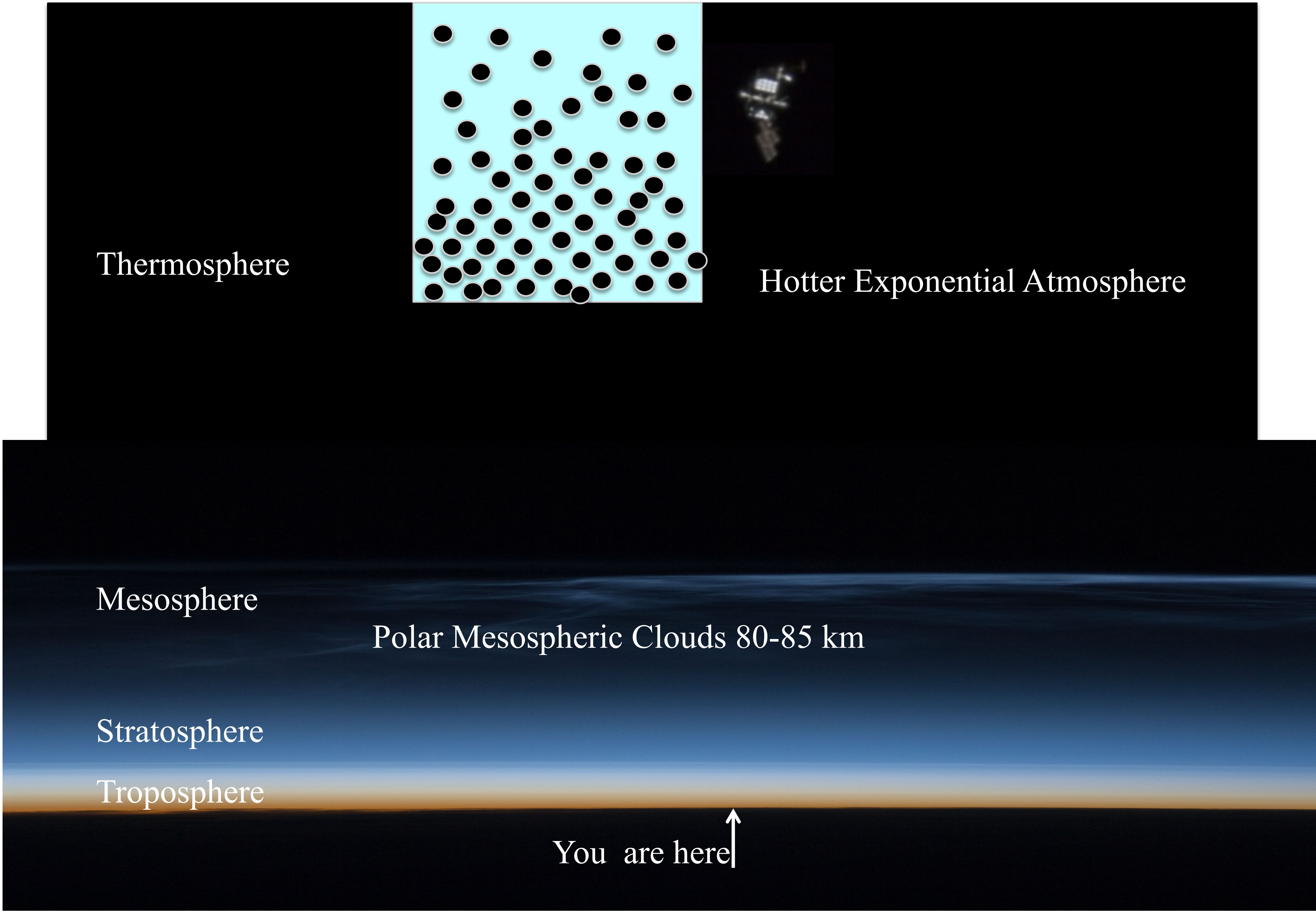
Extreme Geomagnetic Activity Indicated by Auroral Currents

Rate of Orbital Period Change



Sputnik Orbital Period Variation vs Day of July 1958

From Prolss (2011) after Data from Jacchia 1959



Thermosphere
Hotter Exponential Atmosphere
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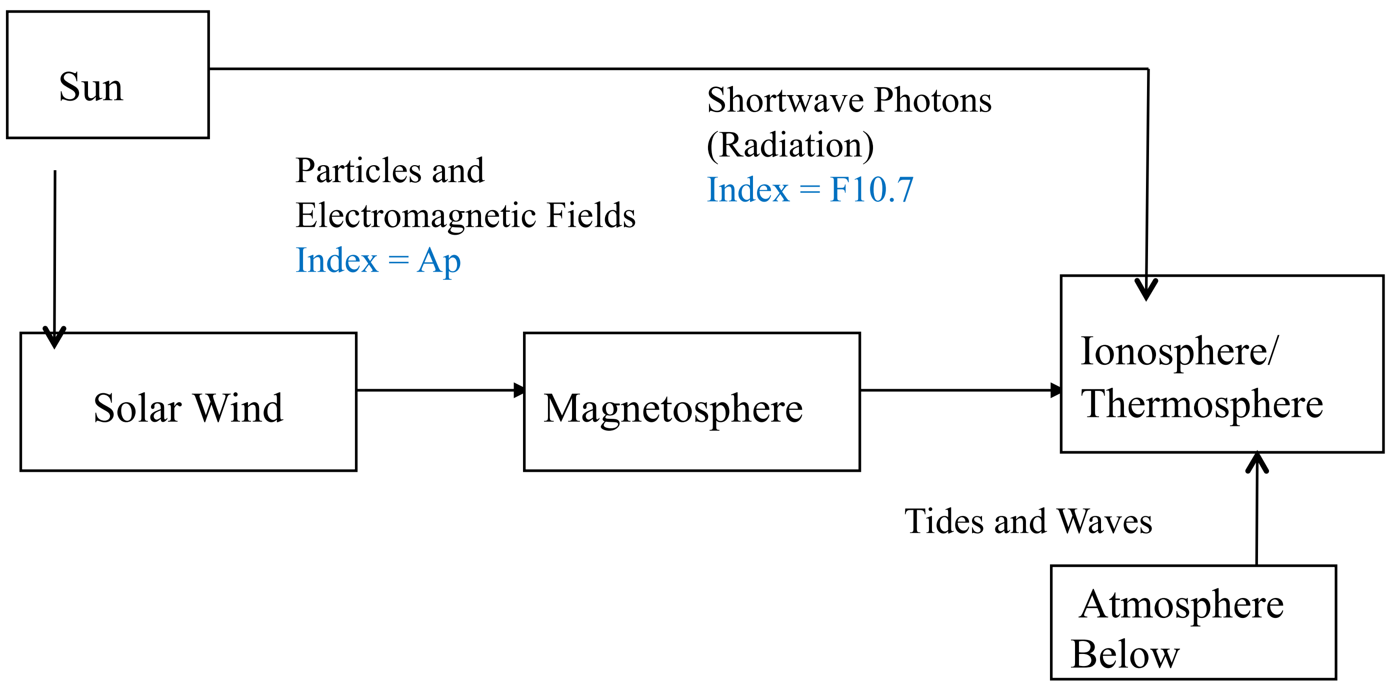
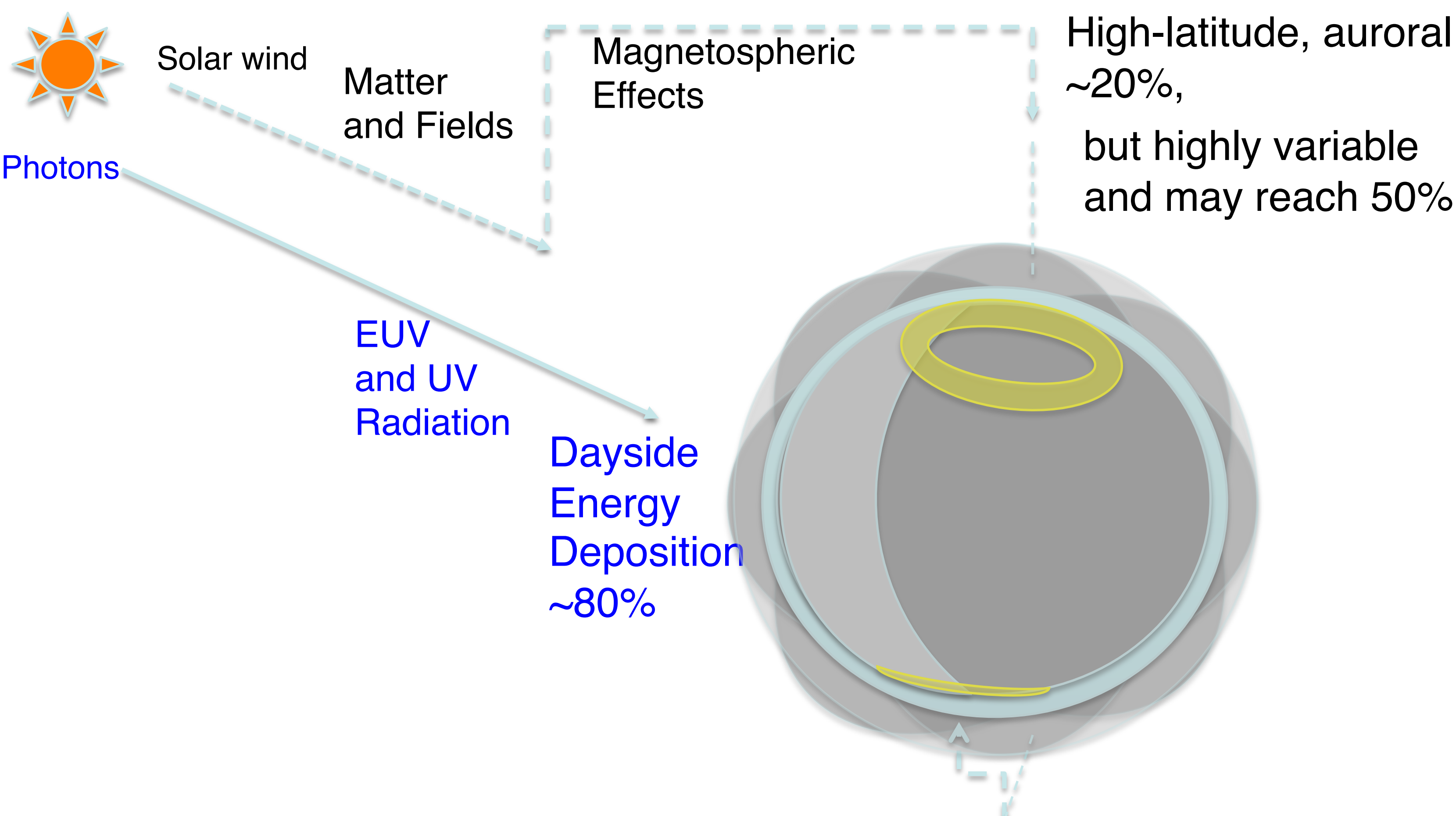
Polar Mesospheric Clouds 80-85 km
Stratosphere
Troposphere
You are here

Energy Flow to the Thermosphere



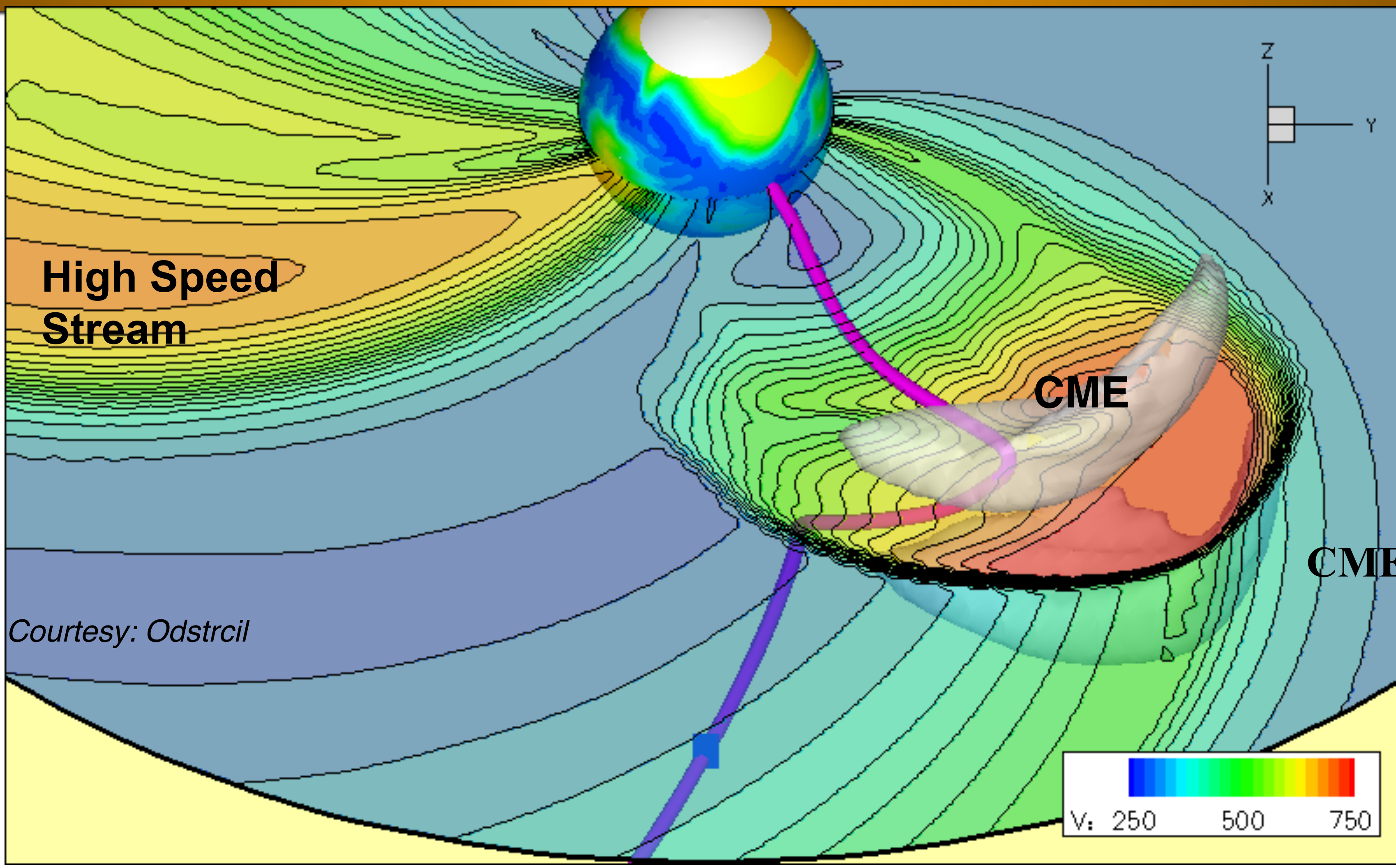
Knipp 2011 Understanding Space Weather and the Physics Behind It

Solar /Solar Wind Energy Deposition



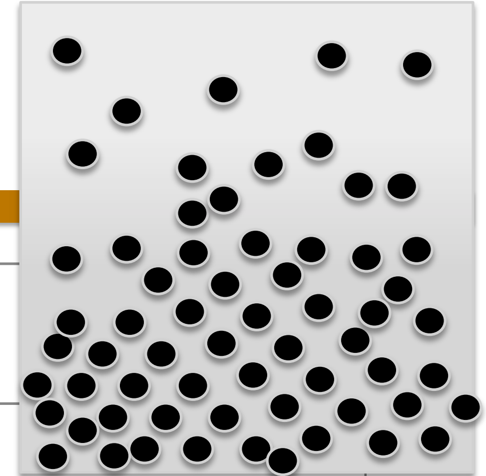
After Prolss, 2011

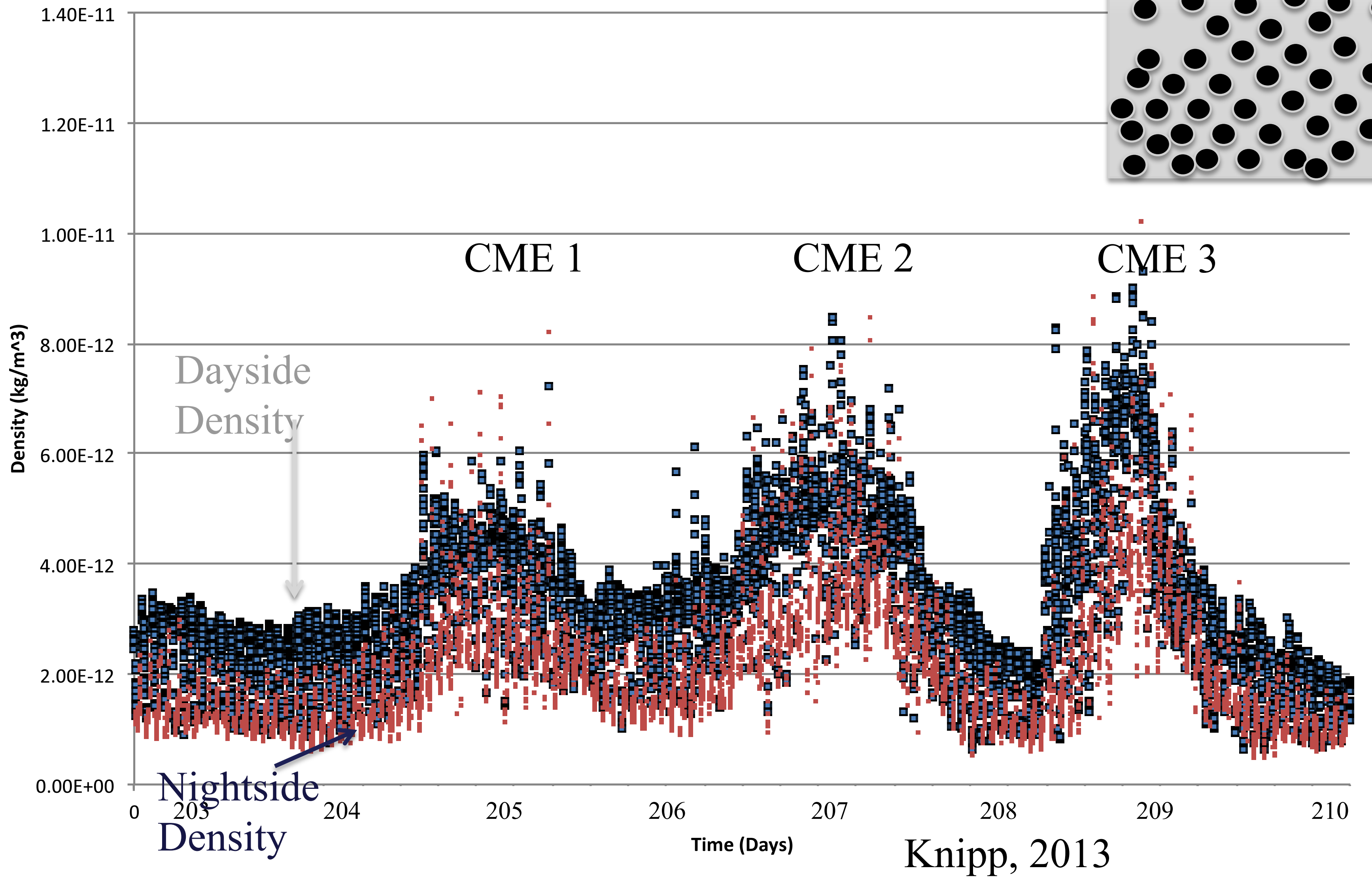
CMEs and HSS Indirectly Heat the Thermosphere



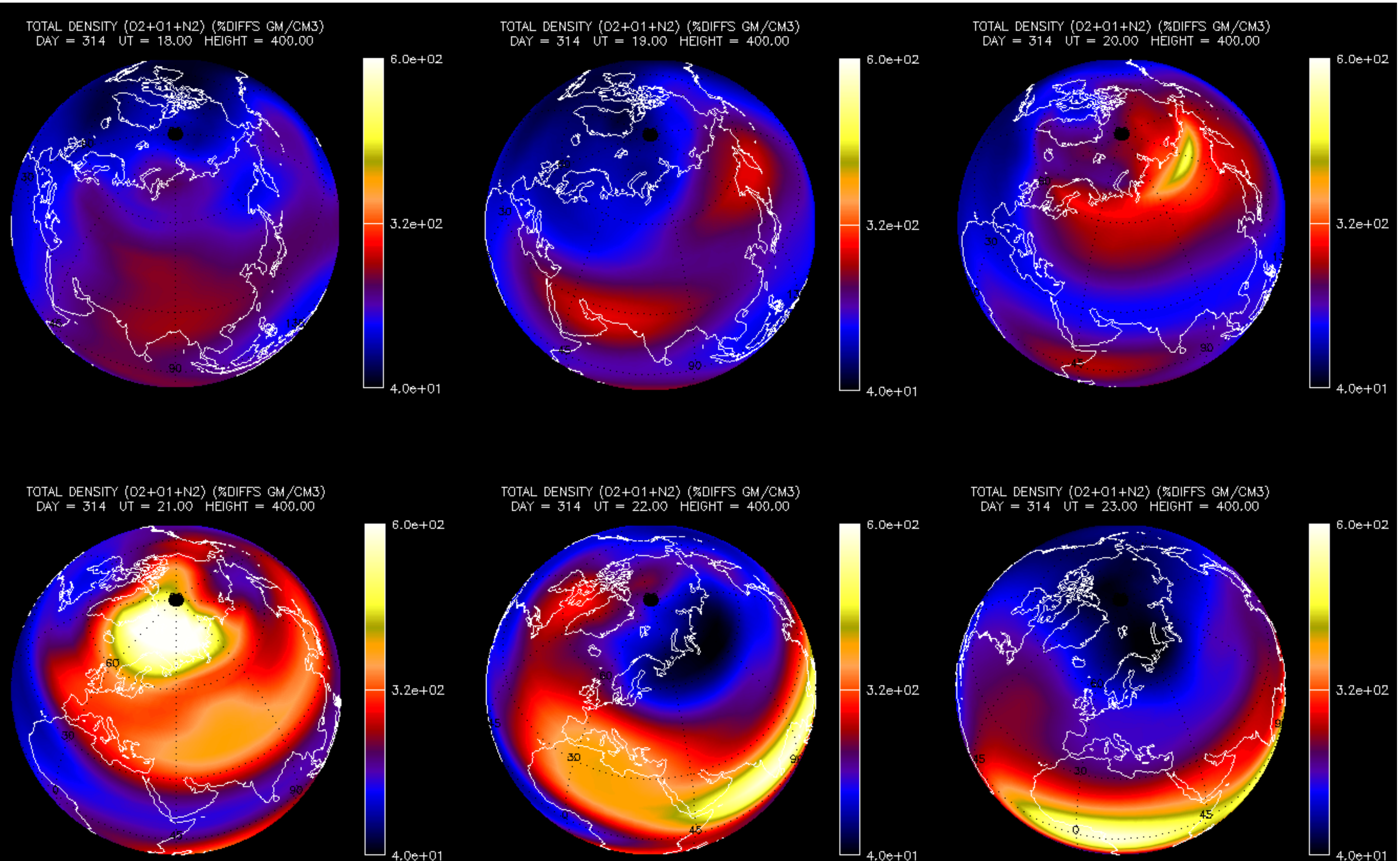
CMEs: extreme short-lived heating, HSSs: Moderate long-lived heating

CHAMP Density Extrapolated to 400 km (ng/m³)

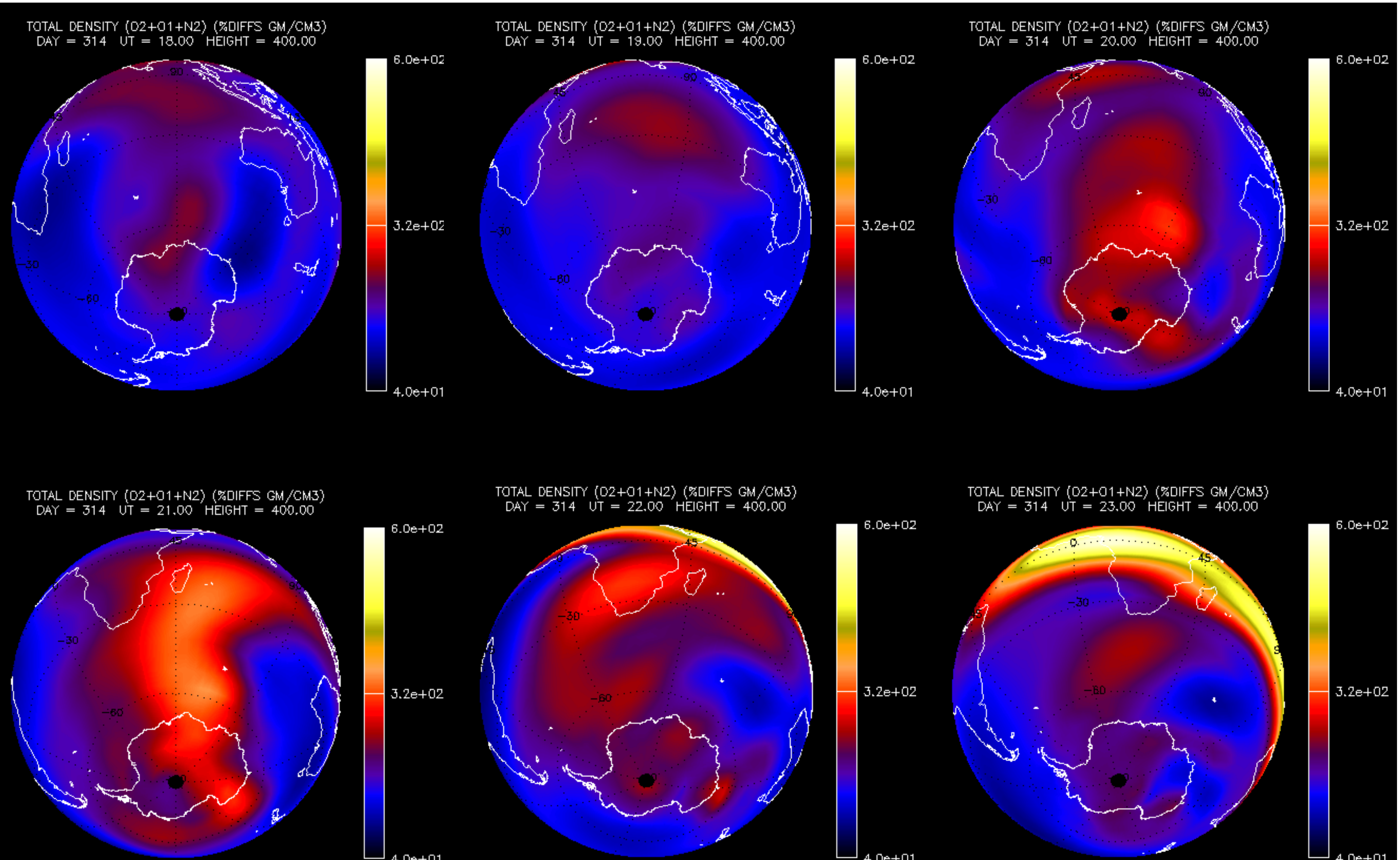




Energy deposition causes atmospheric expansion; Heated molecules and atoms, fighting for more room, migrate upward

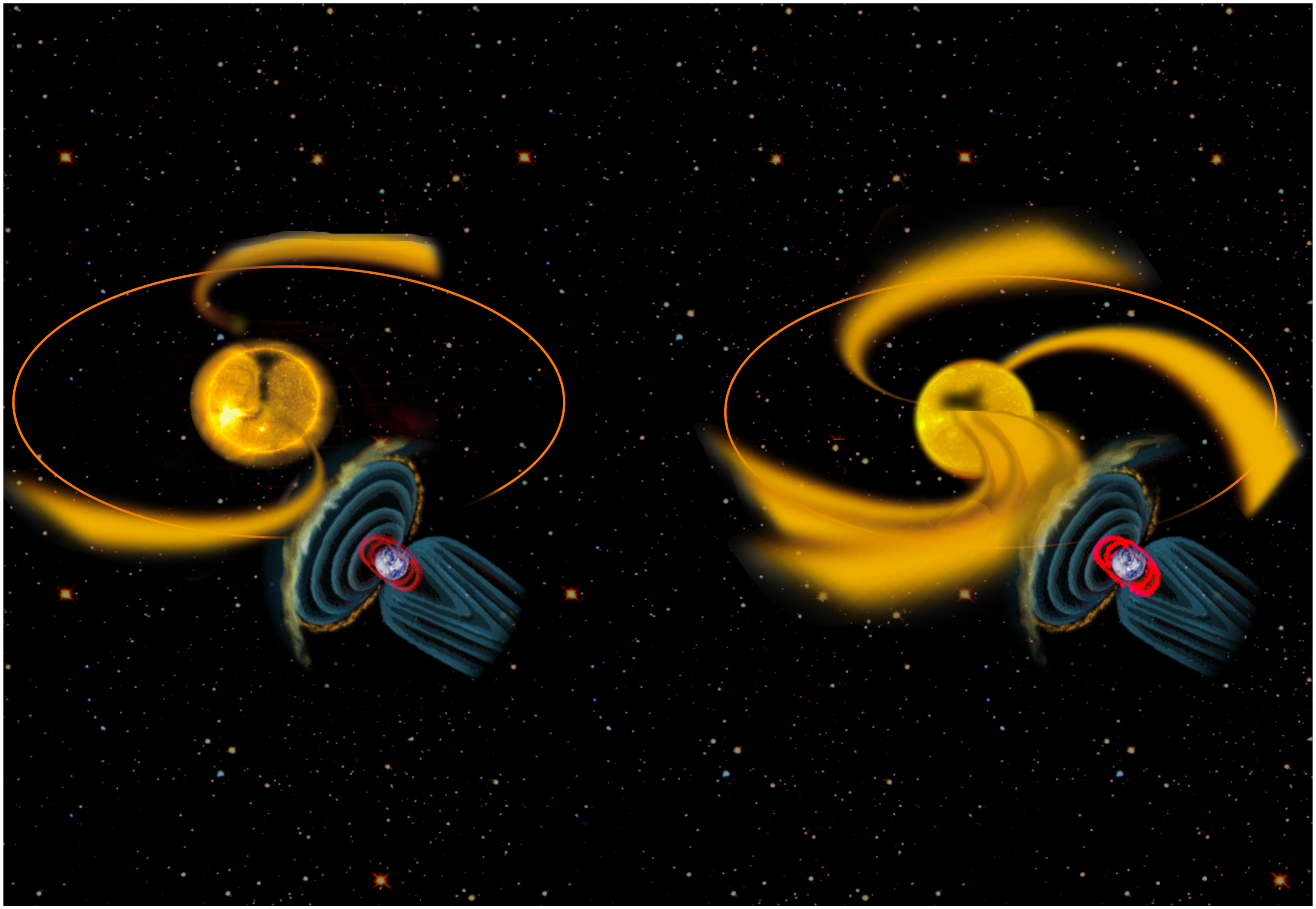


Model output of neutral density change (in %) at 400 km in northern hemisphere during a storm
Atmosphere becomes structured at a fixed altitude. Courtesy of G. Lu, NCAR



Model output of neutral density change (in %) at 400 km in southern hemisphere during a storm
Atmosphere becomes structured at a fixed altitude. Courtesy of G. Lu, NCAR

High Speed Streams Repetitively Heat the Thermosphere



Gibson et al., 2009

2005 Periodograms – High Speed Streams
Subharmonics of a Solar Rotation

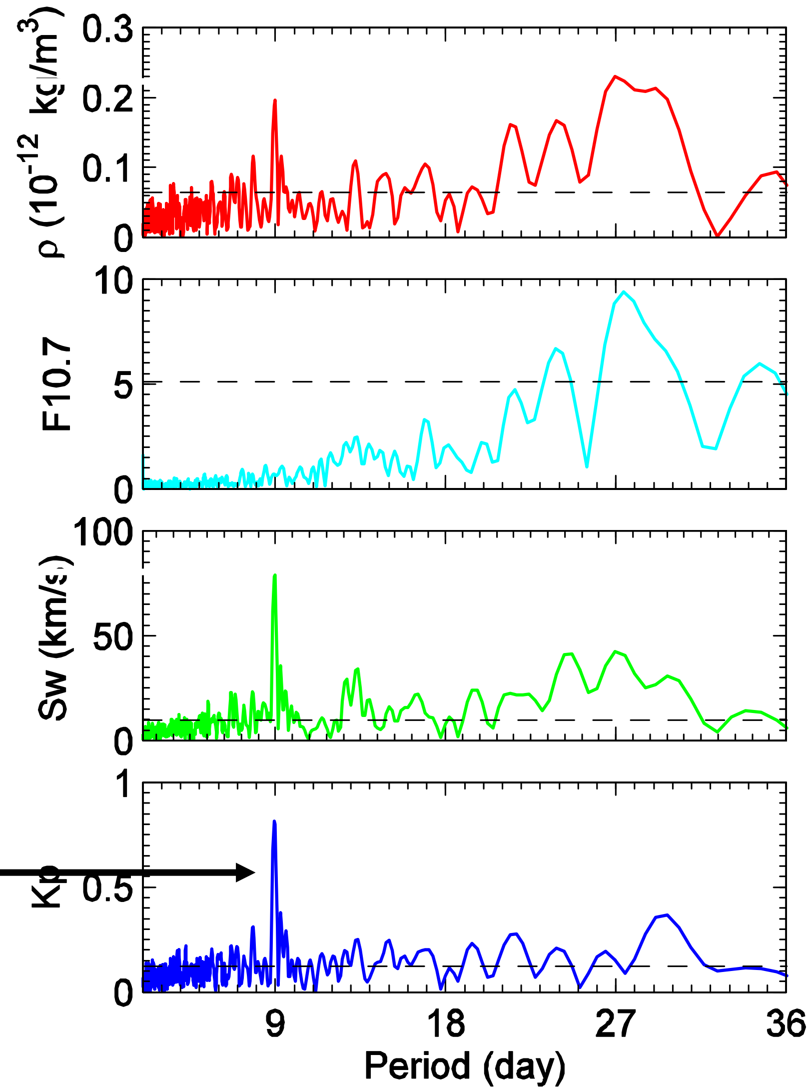
Density - 400km altitude

Solar EUV flux index

Solar wind speed

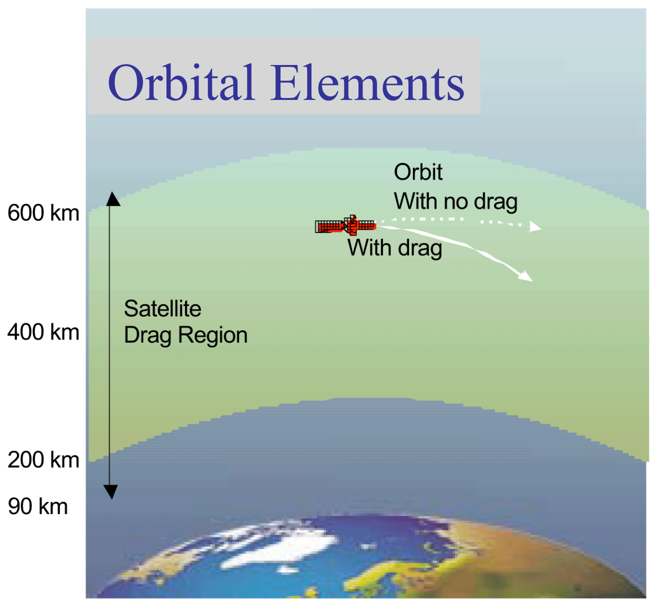
Geomagnetic Activity Index

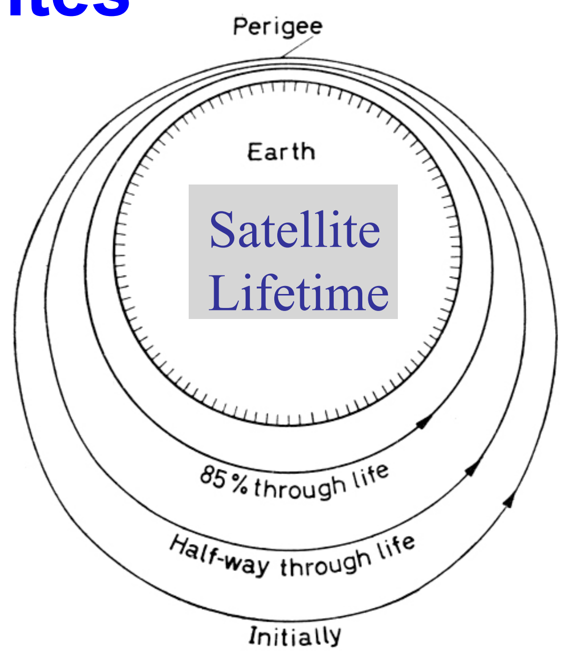
27 days/3

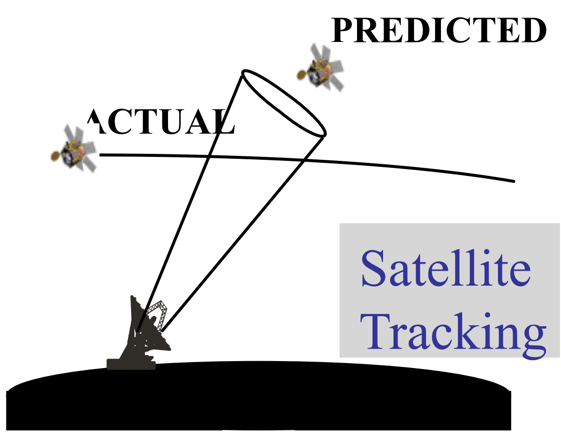


Thayer et al., 2008

Atmospheric Drag on Satellites







Collision Avoidance

- If a predicted conjunction between orbiting objects and the ISS yields a probability of collision greater than 10^{-4}, official flight rules call for the execution of a collision avoidance maneuver by the ISS. Conjunction volume is: 4km x 50km x 50km box

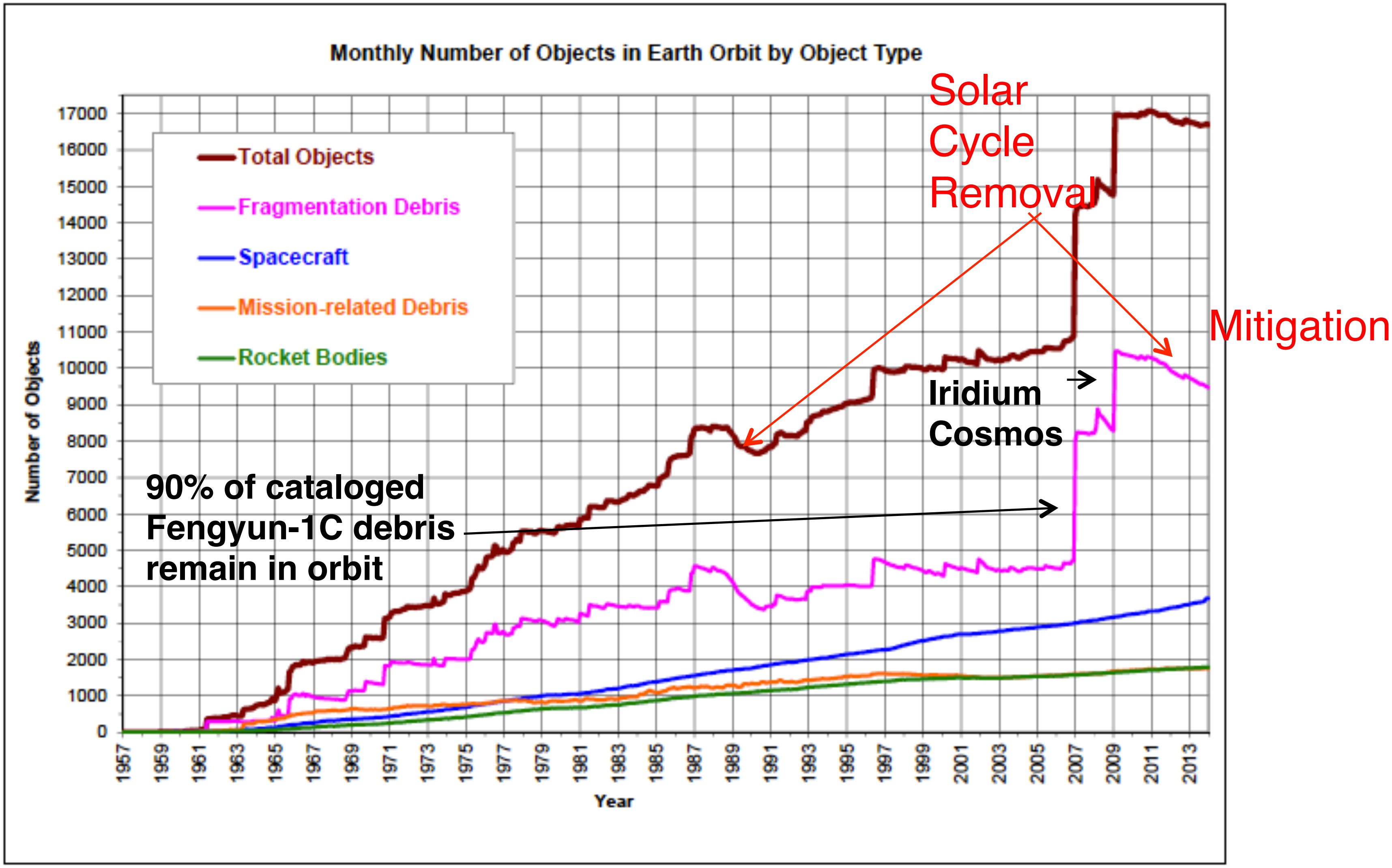
- During its first 15 years of operations, the ISS successfully conducted 16 collision avoidance maneuvers, and on a separate occasion in 1999 a planned maneuver attempt failed.

- In addition, three incidents arose when insufficient time permitted a collision avoidance maneuver, forcing the crew of the ISS to retreat to the Soyuz return craft where they were prepared to undock from the ISS quickly in the event of a collision.

- In total, the collision avoidance maneuver threshold level has been reached only 20 times for an average of once per year.

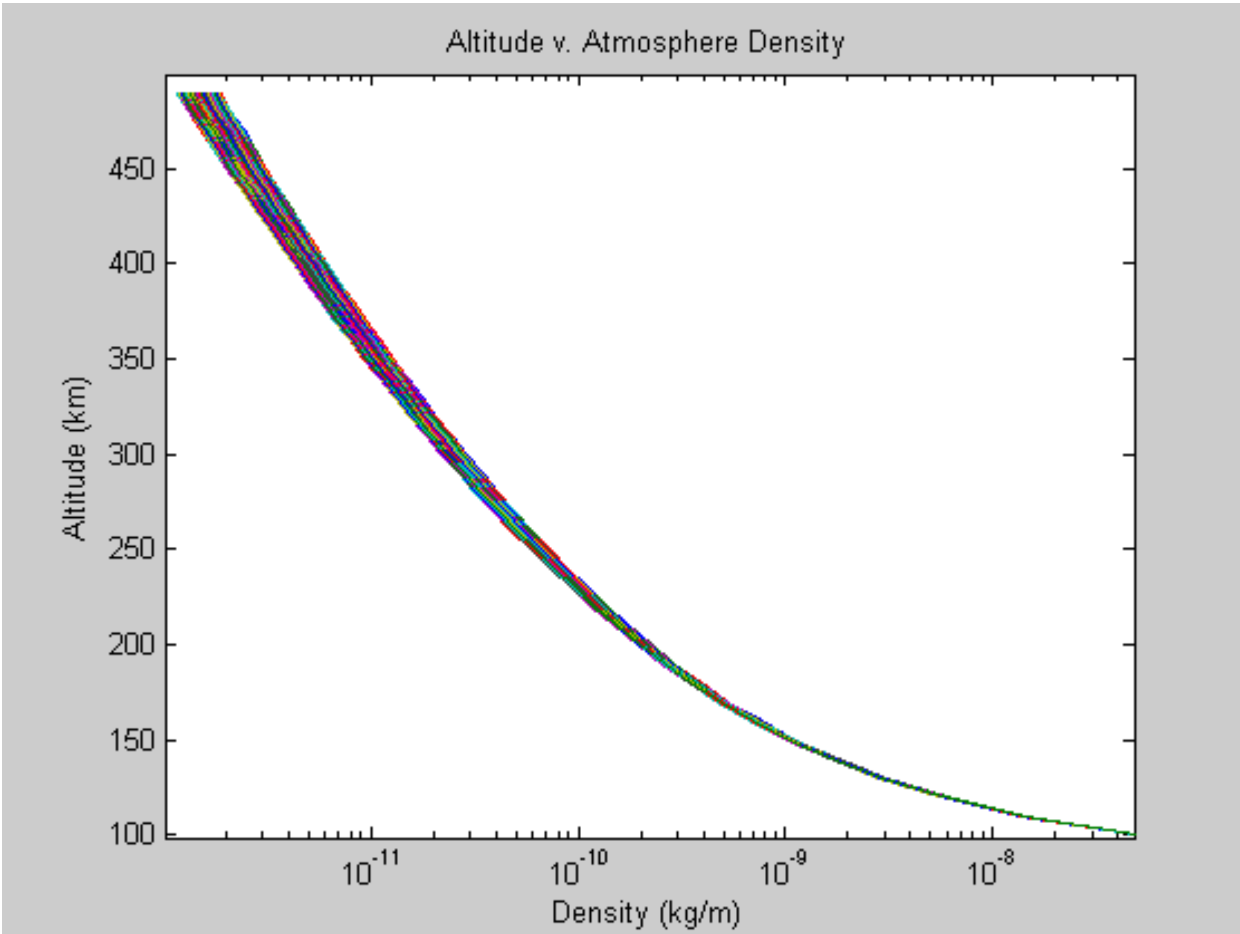
www.nasa.gov http://orbitaldebris.jsc.nasa.gov/

Orbital Debris Quarterly News Vol 18, Jan 2014

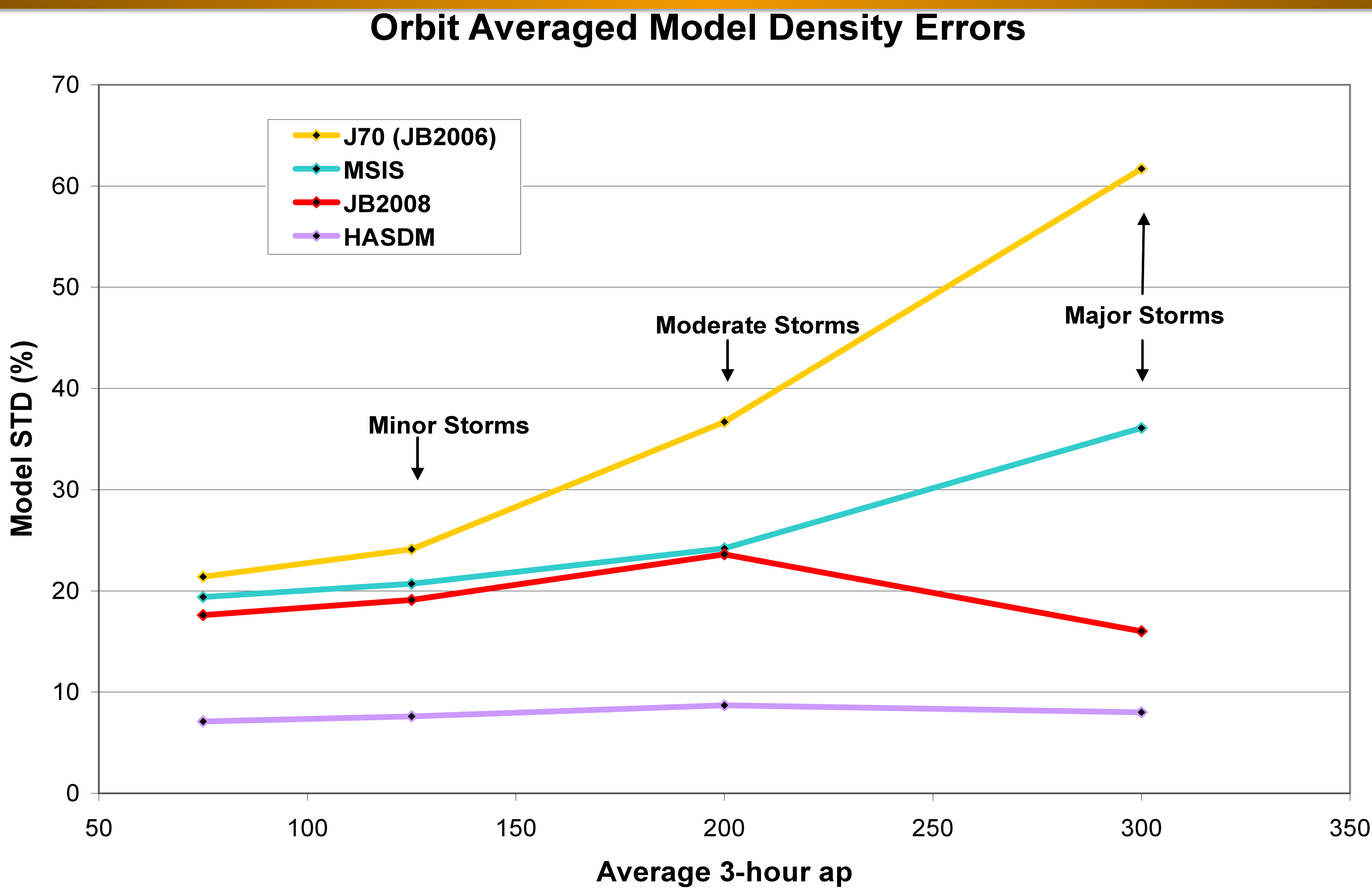


Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Model output from Thermosphere Ionosphere Electrodynamics General Circulation Model Available from CCMC



Jacchia Bowman 2008 Geomagnetic Storm Model Errors



Jacchia Bowman 2008 Model Information

JB2008 **The Jacchia-Bowman 2008 Empirical Thermospheric Density Model** SET

[Home] [Intro] [Indices] [Code] [Publications] [Contacts] [Figures] [SET/Spacewx]

Dear Colleague,

Welcome to the JB2008 empirical thermospheric density model website. Please provide your name and email address if you desire to be notified about updates to the JB2008 model.

[click here to register for updates] *

Please note that cookies must be enabled in your Browsers Preferences to register. Your local installation may have firewall implementations that prevent cookies or Java servlet protocols, in which case you should email spacenvironment@spacenvironment.net with "JB2008" in the subject line to receive updates.

Thank you,

Space Environment Technologies

Last Website Update 6 Oct 2008

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Summary

Significant Challenges are posed by satellite drag

Track and identify active payloads and debris

Collision avoidance and re-entry prediction

Attitude Dynamics

Constellation control

“Drag Make-Up” maneuvers to keep satellite in control box

Delayed acquisition of SATCOM links for commanding /data transmission

Mission design and lifetime

JB2008 Geomagnetic Storm Modeling

All previous empirical models use ap geomagnetic index for storm modeling

The 3-hour ap is a measure of general magnetic activity over the Earth, and responds primarily to currents flowing in the ionosphere and only secondarily to magnetospheric variations

The ap index is determined by observatories at high latitudes which can be blind to energy input during large storms (Huang and Burke, 2004)

The Disturbance Storm Time (Dst) index is primarily used to indicate the strength of the storm-time ring current in the inner magnetosphere

During the main phase of magnetic storms, the ring current becomes highly energized and produces a southward-directed magnetic field perturbation at low latitudes on the Earth's surface

The Dst index is determined from hourly measurements of the magnetic field made at four points around the Earth's equator

JB2008 Dst Equation Development

The thermosphere acts during storm periods as a driven-but-dissipative system whose dynamics can be represented by a differential equation

The driver is the magnetospheric electric field. Burke (2008) determined the relationship for the exospheric temperature responses as a function of Dst:

$$dTc_1 = \left(1 - \frac{1}{\tau_1}\right) dTc_0 + S\left(Dst_1 - \left(1 - \frac{1}{\tau_2}\right) Dst_0\right)$$

- τ parameters are empirically determined relaxation constants
- The above equation must be integrated from storm beginning throughout the entire storm period in-order to compute ΔTc at every point during the storm
- The above equation was optimized to fit the CHAMP and GRACE accelerometer density data, along with HASDM global densities.
- Additional optimized equations based on different τ values were developed for use during the Dst recovery phase period